Sustainability-oriented prioritization of nuclear fuel cycle transitions in China: A holistic MCDM framework under uncertainties

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Abstract

A sustainability-oriented assessment of the nuclear energy system can provide informative and convincing decision-making support for nuclear development strategies in China. In our previous study, four authentic nuclear fuel cycle (NFC) transition scenarios were proposed, featuring different development stages and exhibiting distinct environmental, economic, and technical characteristics. However, because of the multiple and often conflicting criteria embedded therein, determining the top-priority NFC alternative for a sustainability orientation remains challenging. To address this issue, this study proposed a novel hybrid multi-criteria decision-making framework comprising fuzzy Analytic Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)-Geometrical Analysis for Interactive Aid (GAIA), and MOORA. Initially, an improved fuzzy AHP weighting model was developed to determine criteria weights under uncertainty and investigate the influence of various weight aggregation and defuzzification approaches. Subsequently, PROMETHEE-GAIA was used to address conflicts among the criteria and prioritize alternatives on a visualized k-dimensional GAIA plane. As a result, the alternative for direct recycling pressurized water reactor spent fuel in fast reactors is considered the most sustainable. Furthermore, a sensitivity analysis was conducted to examine the influence of criteria weight variation and validate the screening results. Finally, using MOORA, some significant optimization ideas and valuable insights were provided to support decision-makers in shaping nuclear development strategies.

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1. Introduction

To alleviate global climate changes and control temperature variations within 1.5–2 °C by the end of the 21st century, China needs to shift its current energy paradigm from carbon-intensive fossil fuels to carbon-neutral energy-based systems [1-3]. As the only clean, low-carbon, safe, and high-efficiency basic load energy, nuclear energy is a suitable potential option for meeting the CO_2 reduction targets unveiled in the latest 14th Five-Year Plan proposed by China [4,5]. However, considerable uncertainties, such as environmental preservation, economic development, and technical obstacles (E-E-T), arise regarding the future of nuclear energy. In terms of multidimensional development barriers, the security, efficiency, and sustainability of current nuclear energy systems (NESs) should be improved. The nuclear fuel cycle (NFC), which combines a series of industrial processes that describe uranium throughout its life cycle, i.e., from mining to disposal, is the physical basis for NESs. To achieve nuclear sustainability, many countries have devoted collaborative efforts to evaluating different NFC paths. The International Atomic Energy Agency initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and assessed the sustainability of numerous NESs by considering benefit, responsibility, and sustainability as the basic principles [6-9]. An "INPRO Methodology" has also been developed to evaluate NES integrated with an elaborated indicator system from seven different perspectives including safety, environment, economics, infrastructure, waste management, physical protection, and proliferation resistance. The U.S. Department of Energy's Office of Nuclear Energy chartered an evaluation and screening study on its national situation to concretize the latent benefits and risks of all possible NFC options [10-12].

Thus far, several studies on assessing NFC systems using INPRO indicators and methodologies have been conducted [9,13,14]. However, some of these indicators are interconnected and often conflicting, rendering further assessment to be a complex multi-criteria decision problem. Multi-criteria decision-making (MCDM) methods provide a potential tool for decision-makers (DMs) to highlight internal conflicts and explore trade-offs during the decision-making process [15]. Among various MCDM techniques, the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is well-known in the energy sector [16-18]. Despite the significant progress achieved, PROMETHEE II is still mostly applied to rank alternatives for complete ordering based on net outranking flow values in the PROMETHEE family [18]. Notably, an improved PROMETHEE geometrical analysis for interactive aid (GAIA) method descriptively compensates for the limitations of PROMETHEE II due to information loss and provides an excellent graphical representation for DMs to visualize the decision problem on a GAIA plane [19,20]. This exposes the critical aspects of the decision-making problem and helps DMs identify the

best compromise solutions. However, a major limitation of the PROMETHEE method is that DMs are expected to determine all the weights of each criterion in advance [21].

The Analytic Hierarchy Process (AHP) is a universal method for assigning criteria weights by establishing a relatively important degree [22-24]. It is a potential tool for breaking down complex decision problems into simpler ones using a unidirectional hierarchical relationship among decision levels. In many real-world situations, DMs often provide judgments with natural language. The absence of complete information and vague or indefinite meanings in their judgments may lead to inaccurate decision-making results [25]. To address this issue, the introduction of fuzzy set theory has proven instrumental in aiding DMs in quantitatively addressing vagueness, uncertainty, and imprecision in MCDM problems by transforming linguistic terms into fuzzy numbers [26]. Several studies have extended MCDM methods to fuzzy environments [27,28]. For example, Li et al. [29] adopted a fuzzy AHP to determine the weights for reducing the chance of unsafe behavior during nuclear decommissioning. Erdoğan et al. [30] combined fuzzy AHP and fuzzy Technique for Order Performance by Similarity to Ideal Solution to select the best region for nuclear power plants (NPPs) in Turkey.

The combination of fuzzy theory and AHP was motivated by the need to address subjective uncertainties in weight assignment [31]. The effectiveness and potential of this combination have been demonstrated through its extensive application in various fields [32-35]. However, studies that have thoroughly reviewed and discussed procedural variations in fuzzy AHP models are scarce. Such negligence may result in a cumulative effect as different procedure results add up successively to form the consequence of discrepancies in the overall weights. Therefore, this study proposed a novel integrated fuzzy AHP weighting model to enhance robustness and accuracy under uncertainty while mitigating the decision-making bias caused by methodological pitfalls. Furthermore, we explicitly compared the discrepancies arising from various step-by-step procedure-selection methods within the fuzzy AHP model. The newly proposed model advances the understanding of fuzzy AHP and improves the reliability and validity of weight assignment.

Multi-objective Optimization based On Ratio Analysis (MOORA) is an emerging MCDM technique, which was constructed with a foreknowledge of the inherent weaknesses of each conventional method [36]. It possesses high potential for the comprehensive evaluation of alternatives confronting considerable diversity and multiplicity of effective factors. In addition to its wide application in occupational risk assessment, supplier selection, and many other fields, MOORA is also referred to as an efficient multi-objective optimization approach for solving the

trade-offs in complex decision-making problems [32,37-39].

Therefore, combined with good practices and key lessons learned from resourceful studies, this study aims to comprehensively assess potential NFC paths in China and screen out an appropriate transition alternative for future sustainability-oriented NESs. As a continuation of our previous work [31,40-42], this study proposes a novel hybrid MCDM framework to evaluate the sustainability of four candidate NFC alternatives using a specific E-E-T criteria system. Specifically, an improved fuzzy AHP method was developed to obtain the weights of different criteria. Subsequently, the PROMETHEE GAIA method was employed to rank candidate alternatives. Finally, an innovative MOORA method was adopted in the nuclear field to provide a detailed comparative evaluation and analyze the system optimization potential. The novelties of this study are summarized as follows:

- Comparing the outcomes of different procedural methods involved in fuzzy AHP and investigating their influence on the distribution of criteria weights.
- Facilitating an intuitive understanding of the complex interdependencies and tradeoffs among alternatives and criteria on a visualized k-dimensional GAIA plane.
- Providing ongoing efforts to support the formulation of nuclear development strategies by considering the unique characteristics and challenges of the current development status.

2. Methods

MCDM methods provide significant assistance to DMs in effectively evaluating complex multiple-energy alternatives. This assistance facilitates the comparison and ranking of decision-making schemes by considering component interconnections and indicator conflicts from various information channels. Typically, a comprehensive MCDM framework comprises four main sections: (1) identification of relevant alternatives and criteria; (2) determination of criteria weights; (3) ranking of selected alternatives using sensitivity analysis; and (4) providing suggestions for decision-making optimization. Figure 1 shows the overall process of the MCDM framework used in this study.

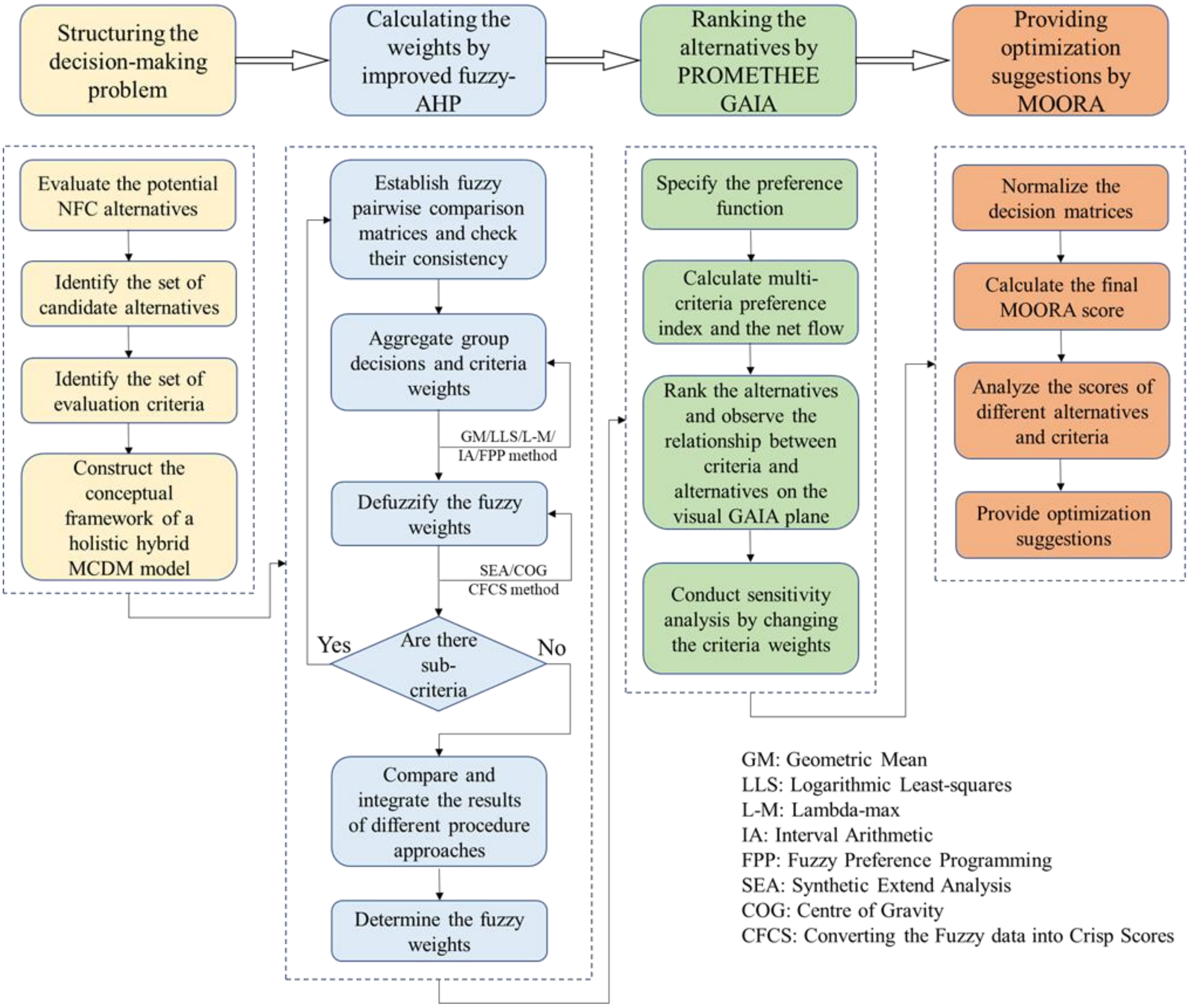


Figure 1 Overall process diagram of the proposed MCDM framework

2.1 NFC transition alternatives and assessment criteria

In our previous study, we developed a dynamic model to analyze the quantitative performance of China's future NFC transition from existing to advanced energy systems through 2100 [31,40-42]. The MCDM framework uses model performance to present an integrated holistic evaluation of representative NES scenarios for sustainability orientation in China. The four proposed candidate NFC transition alternatives are as follows: Alternative 1 (A1) involves a once-through (OT) fuel cycle, wherein uranium–plutonium oxide (UOX) fuels are consumed in both pressurized water reactors (PWRs) and pressurized heavy water reactors (PHWRs) without recycling the spent fuel; Alternative 2 (A2) maintains an OT fuel cycle in a PHWR. Here, the PWR spent fuel discharged from Al is reprocessed and reused in the PWR in the form of mixed uranium–plutonium oxide (MOX) fuels; Alternative 3 (A3) involves reprocessing of the MOX spent fuel discharged from A2 and multi-recycling of the resulting plutonium

(Pu) in a fast reactor (FR); Alternative 4 (A4) involves reprocessing of the PWR spent fuel discharged from Al, followed by direct recycling in an FR, as shown in Figure 2.

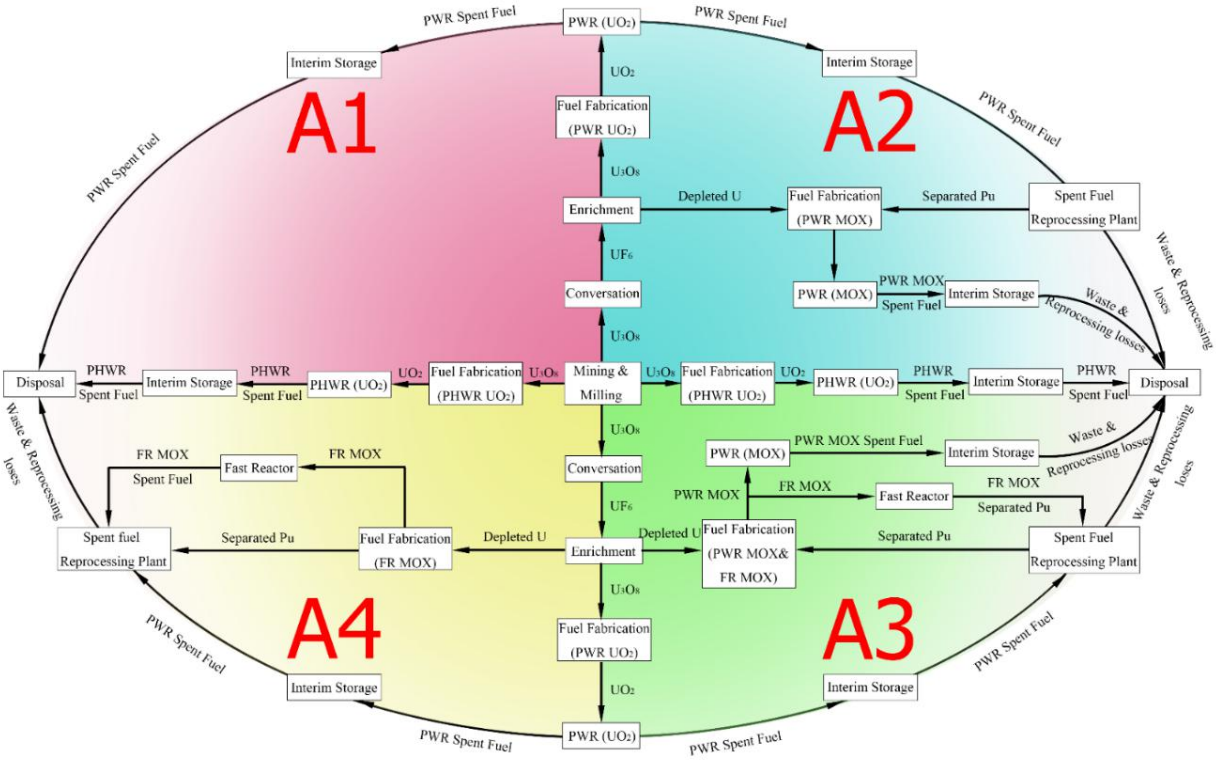


Figure 2 NFC diagram of four candidate alternatives

We also identified six sustainability-oriented main criteria (MC) and 12 sub-criteria (SC) from the perspective of E-E-T to establish a suitable criteria system for evaluating the comprehensive sustainable performance of China's potential NFC alternatives, as shown in Figure 3.

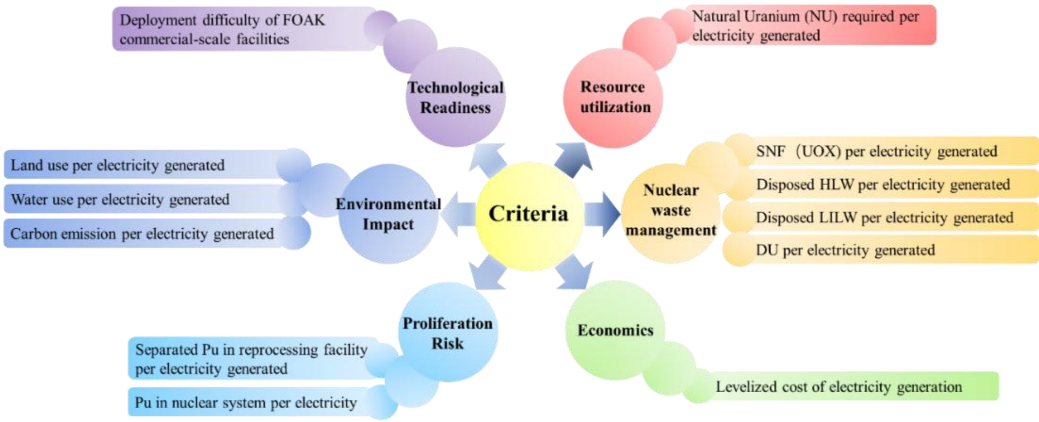


Figure 3 Sustainability-oriented main criteria and sub-criteria

2.1.1 Resource Utilization (MC1)

MC1-Resource utilization indicates the amount of natural uranium (NU) feed during an NFC process. This value is determined by calculating the *NU required per electricity generated* (SC11), thus strategically measuring how effectively NU resources are consumed and utilized against the capacity in a certain NES. This is an important factor that influences nuclear energy utilization and sustainable development.

2.1.2 Nuclear Waste Management (MC2)

Most nuclear waste generated from NFC activities is radioactive and none of the untreated waste is discharged directly. This radioactive waste is typically classified based on its level of radioactivity into low- and intermediate-level waste (LILW) and high-level waste (HLW). Here, four parts of nuclear waste management criteria were considered in detail: *spent nuclear fuel (SNF) (UOX) per electricity generated* (SC21), *disposed HLW per electricity generated* (SC22), *disposed LILW volume per electricity generated* (SC23), *and disposed depleted uranium (DU) per electricity generated* (SC24).

2.1.3 Economics (MC3)

MC3-Levelized cost of electricity (LCOE) is often used as a convenient summary measure to compare the overall economic competitiveness of different electricity-generating technologies. It refers to the revenue estimates used for plant construction and operation during a specified cost-recovery period [43]. In this study, LCOE was selected as the representative SC of economic criteria. It involves two major parts: Levelized reactor cost (LRC), which considers capital investment cost, operation, and maintenance cost, as well as decommission and decontamination costs, and levelized fuel cycle cost (LFCC), which consists of the process costs of front-end and back-end fuel

cycles for an alternative system.

2.1.4 Proliferation Risk (MC4)

With the growing threat of terrorism in recent years, nuclear security has become increasingly important. Nuclear proliferation refers to the potential risk that nuclear materials are illegally diverted to nuclear weapons or other explosive nuclear devices [44]. Thus, sufficient efforts are required from the international community to eliminate proliferation risks and security threats. Notably, the key risk lies with the NFC process, especially some NFC paths involving spent fuel reprocessing [45]. Here, proliferation risk was evaluated by tracking and calculating plutonium (*Pu*) *in nuclear system per electricity generated* (SC41) and *Separated Pu in the reprocessing facility per electricity generated* (SC42).

2.1.5 Environmental Impact (MC5)

The advantages of nuclear energy on the environment is an important aspect of sustainability. Nuclear energy contributes significantly to the reduction of carbon and other pollutant emissions. However, small amounts of tangible and intangible pollutants are vented into the environment, as well as certain negative impacts, such as noise pollution, visual pollution, land occupation, and water consumption, on the ecosystem across the lifespan of the NFC. Three aspects were considered to evaluate environmental impact: *land use per electricity generated* (SC51), *water use per electricity generated* (SC52), and *carbon emission per electricity generated* (SC53).

2.1.6 Technological Readiness (MC6)

Technological readiness is a qualitative indicator for estimating the technological maturity of an NFC application at the current stage. It is related to the development phase of energy and infrastructure projects, power efficiency, commercialization scale, and other factors. The *deployment difficulty of FOAK commercial-scale facilities* (SC61) was used to evaluate the technological readiness of NFC alternatives.

2.2 Weights of criteria

As a relative measurement method, AHP applies to ranking multiple alternatives while considering both qualitative and quantitative criteria and can also be used to determine criteria weights. Based on the combination of conventional AHP and fuzzy set theory, a fuzzy AHP method extends the limits of conventional AHP by converting original crisp judgments into fuzzy contexts, effectively addressing uncertainty/obscurity situations in practice. However, the existence of fuzzy sets and intricate associated operations increases the complexity of

programming and calculation. The major procedures of fuzzy AHP are as follows: 1) constructing the decision-making hierarchy, 2) establishing the fuzzy pairwise comparison matrix in terms of fuzzy numbers, 3) aggregating group decisions and computing priority weights, and 4) defuzzifying fuzzy weights and verifying consistency [46]. Notably, no fixed execution sequence exists between aggregation and defuzzification; however, the calculation is simplified if the defuzzification process is performed first. Subsequently, we thoroughly review and compare various approaches for these procedures across the entire fuzzy AHP model.

2.2.1 Triangular Fuzzy Number

Owing to its intuitiveness and computationally efficient representation, the triangular fuzzy number (TFN) is one of the well-known fuzzy numbers for depicting the natural preferences of DMs. The TFN $\tilde{C}$ can be obtained using a triplet $\tilde{C}=(l,m,h)$, where l, m, and u represent the lower, median, and upper membership values, respectively. The membership function can be expressed as

$$\mu(x)=\begin{cases}\dfrac{x-l}{m-l}, & l\le x\le m\\ \dfrac{h-x}{h-m}, & m\le x\le h\end{cases} \tag{1}$$

To present the scale of the elements whose grade of membership is not less than the specified value, α, a crisp value set is defined as

$$\tilde{C}_{\alpha}=\left\{x\,\middle|\,\mu(x)\ge\alpha\right\}, \tag{2}$$

where $\tilde{C}_{\alpha}$ is the α cut set of the fuzzy set $\tilde{C}$. This indicates a confidence interval at the corresponding certitude level α [47]. The α cut set of a TFN can be described naturally using the interval $\tilde{C}_{\alpha}=\left[l+(m-l)\alpha, h-(h-m)\alpha\right]$. The linguistic comparison terms and corresponding fuzzy numbers used in this study are represented in Table 1.

Table 1 Scales of pairwise comparisons of fuzzy AHP

Fuzzy Number	Linguistic Scales	Scale of Fuzzy Number
$\tilde{9}$	Extremely preferred	(8, 9, 10)
$\tilde{7}$	Very strong importance	(6, 7, 8)
$\tilde{5}$	Strong importance	(4, 5, 6)
$\tilde{3}$	Importance	(2, 3, 4)
$\tilde{1}$	Equal	(1, 1, 1)
$\tilde{2},\tilde{4},\tilde{6},\tilde{8}$	Intermediate values between the above	

2.2.2 Aggregation of group decisions and criteria weights

Aggregation is essential for obtaining criteria weights. Appropriate results are generated in the form of a single fuzzy set by aggregating the fuzzy pairwise comparison matrix. Aggregation involves two aspects: synthesizing judgment opinions from multiple experts into a comprehensive comparison matrix and deriving fuzzy criteria weights and alternative priorities. First, different expert judgments may share either common preferences or widely divergent perspectives. Therefore, their opinions should be aggregated to achieve a converged result. The geometric Mean (GM) method is one of the most commonly used methods for group decision aggregation. Then, because the result of group decision aggregation for a single criterion is usually indicated by a mean or average value, a full account of all criteria should be considered to implement weight aggregation. In this study, five methods including the GM, logarithmic least-squares (LLS), lambda-max (L-M), interval Arithmetic (IA), and fuzzy preference programming (FPP) methods are selected. Detailed descriptions of these methods are provided in the Supporting Information (SI).

2.2.3 Defuzzification

Defuzzification is a compulsory method for determining crisp weights because the fuzzy value cannot provide an intuitive comparison result directly. This method translates the fuzzy matrix into a crisp matrix. In this study, the center of gravity (COG), synthetic extension analysis (SEA), and conversion of fuzzy data into crisp cores (CFCS) methods were used to defuzzify fuzzy numbers. The detailed descriptions and steps are provided in the SI.

2.3 Alternative ranking and evaluation

PROMETHEE is more applicable to case studies involving a limited number of alternatives than other popular MCDM techniques. It possesses the advantages of both simplicity and high specificity of outranking relationships with respect to multiple conflicting criteria. By obtaining the preorder of candidate alternatives using the preference function to aggregate leaving and entering outranking flows, PROMETHEE I provides a partial ranking, which may lead to incomparability between some alternatives, whereas PROMETHEE II updates to generate a complete ranking by computing the net outranking flow. The major procedures of PROMETHEE II are described in the SI. The net outranking flow is the balance between exiting and entering flows. This defines the complete preorder of PROMETHEE II, implying that an alternative with a higher net flow would yield a better advantageous sequence.

Although a complete preorder enables DMs to effectively compare all alternatives, some relationship information may be lost during the calculation of net outranking flow. To demonstrate the conflicts and mutual relations among the criteria and alternatives applied to the scores of unicriterion net flow (Table 2), the concept of GAIA was proposed to improve PROMETHEE II using a visually descriptive approach [48].

Table 2 Unicriterion net flow

	ϕ_1	ϕ_2	$\cdots$	ϕ_j	$\cdots$	ϕ_k
a_1	$\phi_1(a_1)$	$\phi_2(a_1)$	$\cdots$	$\phi_j(a_1)$	$\cdots$	$\phi_k(a_1)$
a_2	$\phi_1(a_2)$	$\phi_2(a_2)$	$\cdots$	$\phi_j(a_2)$	$\cdots$	
$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$
a_i	$\phi_1(a_i)$	$\phi_2(a_i)$	$\cdots$	$\phi_j(a_i)$	$\cdots$	$\phi_k(a_i)$
$\vdots$	$\vdots$	$\vdots$		$\phi_k(a_2)\ \vdots$		$\vdots$
a_n	$\phi_1(a_n)$	$\phi_2(a_n)$	$\cdots$	$\phi_j(a_n)$	$\cdots$	$\phi_k(a_n)$

Table 2 presents more information than the conventional multicriteria table owing to the extra consideration of the preference degrees of DMs. $\phi_j(a_i)$ is dimensionless and its value lies between -1 and 1. Each alternative can be shown as a unique point in the k-dimensional space.

GAIA employs the principal components analysis to achieve dimension reduction, which can maintain the integrity of information to the extent possible in the k-dimensional space. The GAIA plane is the best selection to translate

the k -dimensional representation on a two-dimensional plane as it can retain the maximum possible quantity of information, as shown in Figure 4.

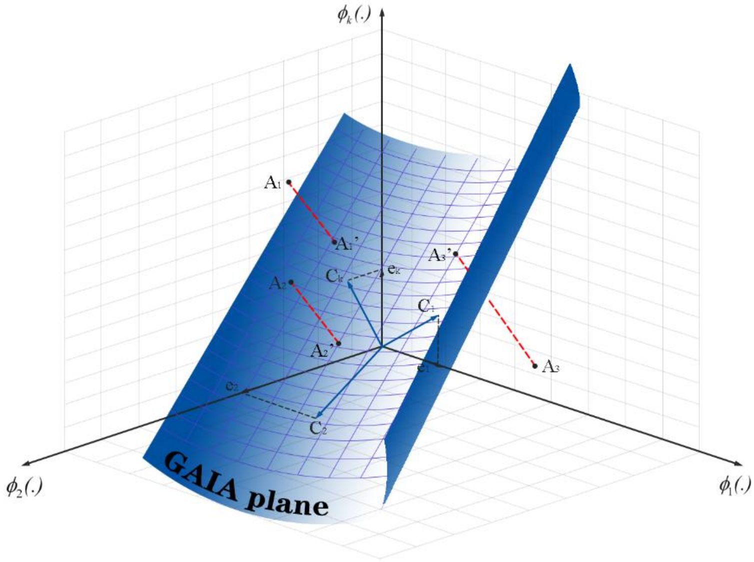


Figure 4 GAIA plane

In the GAIA plane, each point represents an alternative and the axes represent criteria. The decision axis is determined as the weighted result of all criteria axes. Alternatives with similar profiles tend to be closer to each other on the plane, reflecting their shared strengths and weaknesses. Criteria with similar attributes are presented as adjacent axes in the same direction, whereas the axes of conflicting criteria perform in the opposite direction. The length of each axis indicates the weight assigned to the corresponding criterion. When an alternative point is located close to the orientation of a certain criterion axis or several interconnected criteria axes (particularly when it aligns perfectly with an axis), this alternative performs well on those criteria or several interconnected criteria, and vice versa. The decision axis, represented by the projection of the unit vector of the weights, demonstrates the relationship between criteria and PROMETHEE rankings. If a specific criterion is provided for almost all weights, the decision axis coincides with the criteria axis in the GAIA plane. However, the decision axis does not indicate the optimal alternative. Rather, it provides information on the position of the most appropriate alternative relative to the criteria. The orientation and length of a decision axis can change as criteria weights change. This change can thus be considered an indicator to illustrate the type of compromise following multiple measures of performance across all criteria and improve weight assignment. Additionally, the shorter the decision axes in the GAIA plane, the more reliable the decisions, suggesting a significant distinction between alternatives.

Although the GAIA plane covers almost all information, some information may be lost after the projection process.

Set δ as the quantity of information preserved.

$$\delta = \frac{\lambda_1 + \lambda_2}{\sum_{j=1}^{k} \lambda_j} \tag{3}$$

Let the scores of the unicriterion net flow be arranged as a matrix $[M]_{n\times j}$, where $\lambda_1, \lambda_2, \cdots, \lambda_j, \cdots \lambda_k$ is the set of positive eigenvalues of the covariance matrix $M'M$ satisfying the condition $\lambda_1 < \lambda_2 <, \cdots, < \lambda_j <, \cdots < \lambda_k$. Generally, δ exceeds 60% and often 80%. A higher value of δ indicates that concrete and complete structures of MCDM problems were built considering multiple criteria explicitly. When δ decreases to lower than 50%, the reliability of the GAIA plane decreases.

2.4 Decision-making optimization

MOORA is one of the recent MCDM methods proposed by Braorers and Zavadskas [36]. Compared with other conventional techniques, MOORA significantly simplifies mathematical computations and streamlines the overall process while reinforcing the stability of the MCDM framework. The main steps are as follows:

Step 1: Define a decision matrix $F = \left[c_{ij}\right]_{m\times n}$ with m alternatives and n criteria. c_{ij} denotes the value of the i_{th} alternative on the j_{th} criterion.

$$F = \left[c_{ij}\right]_{m\times n} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{12} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} \tag{4}$$

Step 2: Normalize the decision matrix $F = \left[c_{ij}\right]_{m\times n}$ using Eq.5.

$$c_{ij}^* = \frac{c_{ij}}{\sqrt{\sum_{j=1}^{m} c_{ij}^2}} \tag{5}$$

Step 3: Calculate the normalized evaluation value for each alternative by considering all existing alternatives and their weights.

$$y_i^* = \sum_{j=1}^{t} w_j c_{ij}^* - \sum_{j=t+1}^{n} w_j c_{ij}^*, \tag{6}$$

where y_i^* is the final MOORA score for the i_{th} alternative. $j = 1, 2, 3, \cdots, t$ refers to the beneficial criteria,

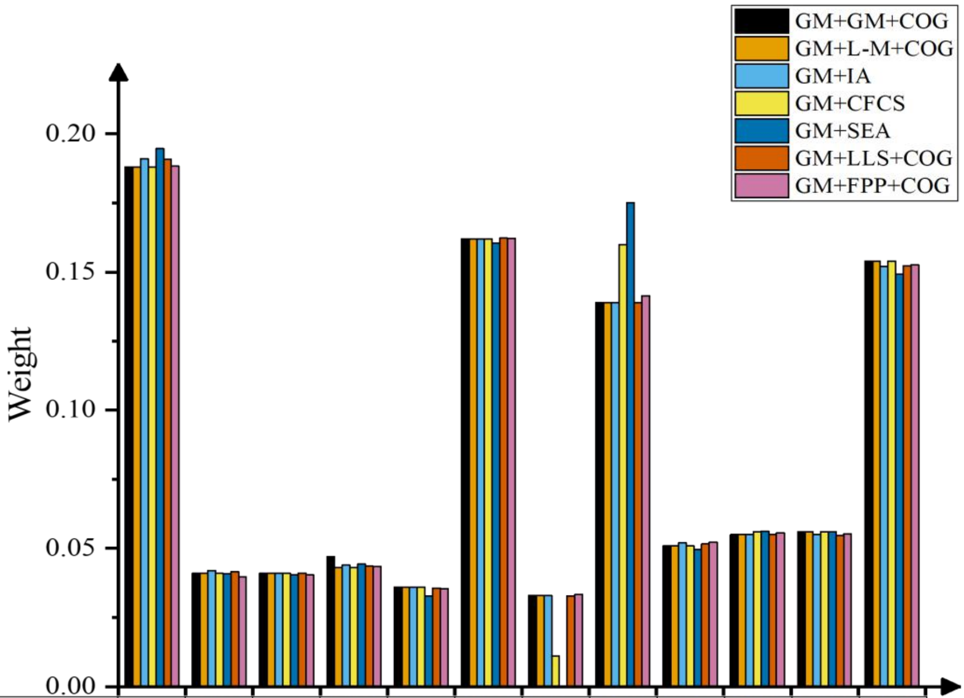
and $j = t+1, t+2, \cdots, n$ refers to the remaining non-beneficial criteria.

3 Results and discussions

3.1 Fuzzy AHP Weights

In this study, a stochastic sampling model was developed to simulate an iterative expert survey process for estimating group decisions. This model incorporates an anonymous iteration method among a panel of simulated experts, underlying the Delphi technique. Significantly, none of the strict guidelines or absolute recommendations have yet defined the most appropriate sample size of panel participants for the Delphi survey, as many Delphi studies used between 30 and 60 panelists [49]. We further analyzed and determined a reasonable sample size for the proposed stochastic sampling model. Unlike expert judgments in practice, the simulated results of the 30-sample size contained the largest diversity with high sampling error. As the sample size increases, the resultant distribution presents a normal distribution with a low standard deviation and broad confidence interval. Finally, we determined the upper limit of the 60-sample size to simulate and collect 60 groups of expert opinions in the form of a pairwise comparison matrix in line with 6 MC and 12 SC. Each selected comparison matrix passed a consistency check because its consistency ratio was less than 0.10.

Figure 5 shows the calculated weights for the 6 MC and 12 SC. Seven sets of final criteria weights were determined using the characteristics of the different procedures used across the entire fuzzy AHP model. For the first four sets, the GM method was first employed to aggregate the fuzzy information from group decisions, followed by weight aggregation via four different methods: GM, L-M, LLS, and FPP. Finally, the TFN weights were defuzzified using the identical COG method. In the latter three sets, the GM method was applied for group decision aggregation and the IA, CFCS, and SEA methods were selected to aggregate and defuzzify the criteria weights. Significantly, the weight of *SC41- Pu in nuclear system per electricity generated* calculated using the SEA method is 0.000. A value of zero indicates that this criterion slightly influences the overall performance. However, its role in the entire evaluation system cannot be ignored because of its zero value.



Methods \ Sub-criteria	SC1-1	SC2-1	SC2-2	SC2-3	SC2-4	SC3-1	SC4-1	SC4-2	SC5-1	SC5-2	SC5-3	SC6-1
GM+GM+COG	0.191	0.141	0.037	0.037	0.035	0.164	0.033	0.139	0.051	0.059	0.061	0.152
GM+L-M+COG	0.191	0.041	0.037	0.038	0.035	0.164	0.033	0.139	0.051	0.059	0.060	0.152
GM+LLS+COG	0.191	0.042	0.041	0.044	0.036	0.162	0.033	0.139	0.052	0.055	0.055	0.152
GM+FPP+COG	0.188	0.040	0.040	0.043	0.035	0.162	0.033	0.141	0.052	0.056	0.055	0.153
GM+IA	0.194	0.042	0.037	0.037	0.035	0.164	0.033	0.139	0.051	0.059	0.060	0.150
GM+CFCS	0.191	0.041	0.037	0.037	0.035	0.164	0.011	0.161	0.051	0.060	0.061	0.153
GM+SEA	0.198	0.041	0.035	0.036	0.032	0.164	0.000	0.175	0.047	0.063	0.064	0.147

Figure 5 Main- and sub-criteria weights under different methods combinations for fuzzy AHP processes

As shown in Figure 5, most SC weights exhibit similarities with slight variations when different aggregation and defuzzification procedures are employed. Although the effect of individual discrepancies may be negligible in many cases, the accumulation of successive and arbitrary discrepancies can have an immeasurable effect on the final MC weights. To address this issue, we proposed an integrated fuzzy AHP weighting approach, which aggregates and averages the different calculated weighting results using the above seven methods to finally integrate criteria weights. This integrated approach can significantly improve the robustness and accuracy of the fuzzy AHP model under uncertainty, effectively eliminating decision-making bias caused by methodological pitfalls. The final criteria weights presented in Figure 6 show that *MC1-Resource utilization* is the most important indicator for ensuring the sustainable development of nuclear energy with a weight of 0.193, followed by *MC4-Proliferation risk* (0.173), *MC5-Environmental Impact* (0.171), *MC3-Levelized Cost of Electricity* (0.164), and *MC6-Technological Readiness* with a weight of 0.151. By contrast, *MC2-Nuclear Waste Management* had the

lowest impact on the overall prioritization of alternatives, with a weight of 0.148. For *MC1-Resource utilization*, although the NU supply is not considered a restrictive factor limiting nuclear energy development in the short term as additional uranium resources are discovered, it is still becoming a prime concern for nuclear sustainability [10,50]. This was directly reflected as a high weighting value of *MC1-Resource utilization*. Compared with other toxic industrial wastes, nuclear waste is neither particularly hazardous nor difficult to manage, and its amount is relatively low. Moreover, the nuclear sector takes full responsibility for the waste. Additionally, safe methods for the final disposal of nuclear waste including LILW and HLW have been technically and contrapunctally proposed in terms of radioactivity. As an international consensus approach to provide safe management of nuclear waste, geological disposal ensures that no harmful contaminants and no radioactivity can leach or migrate from waste repository into ambient environments for hundreds of years. Because future risks cannot easily be assessed, the impact of nuclear waste management criteria is always underestimated. Thus, for *MC2-Nuclear waste management* that gained a relatively low weight in this study, it would be also reasonable. By contrast, moderate weights for the proliferation risk criteria can be derived in response to the immediate consequences of nuclear security incidents and emergencies.

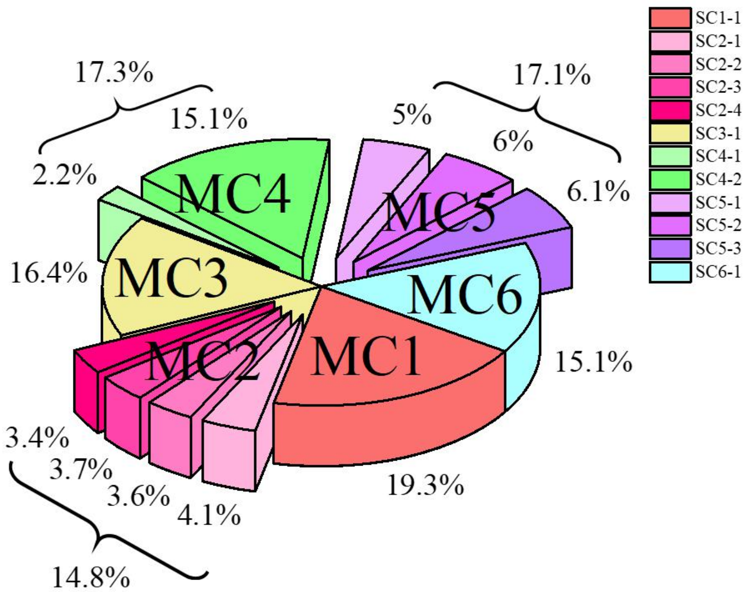


Figure 6 Proportion of the final weights of all criteria

As shown in Figure 6, no extremely high or low weighting value exists, implying that no criterion has an overwhelming importance for nuclear sustainability. This also proves that the proposed fuzzy AHP model and data are reasonable and reliable.

3.2 PROMETHEE GAIA

In this study, we intend to incorporate currently available modeling techniques into a novel hybrid MCDM framework to evaluate the sustainability of four candidate NFC alternatives using a specific E-E-T criteria system. After the identification of the 6 relevant MC and 12 SC, all quantitative performance indicators were linked with the output data of the four reference fuel cycle scenarios simulated to build a system evaluation metric of the MCDM framework. Notably, the specifics of the first stage for structuring the decision-making problem of the proposed MCDM framework (as shown in Figure 1) were elaborated in a separate study [40]. Table 3 presents the performance metrics of the criteria system for the four fuel cycle alternatives. In addition, the details of the material and energy flow modeling (e.g., the design specifications and parameters of the reference nuclear reactors, time factor assumption, and deployment rate of nuclear facilities) and the related performance analysis can be found in our previous studies [31,40-42]. A weighted decision matrix can be derived by combining the fuzzy AHP weights and performance data. Because all the criteria have been unified into cost-type attributes, where lower values yield better performance, the weighted decision matrix was directly normalized using the linear min-max normalization method. Subsequently, an alternative screening and ranking process was performed using PROMETHEE GAIA.

Table 3 Performance indicator metrics of the four nuclear fuel cycle alternatives

Criteria	Resource Utilization	Nuclear Waste Management				Economics	Proliferation Risk		Environmental Impact			Technological Readiness
Sub-criteria	NU required per electricity generated	SNF (UOX) per electricity generated	Disposed HLW per energy generated	Disposed LILW volume per energy generated	Disposed DU per energy generated	Levelized cost of electricity generation	Pu in nuclear system per electricity generated	Separated Pu in reprocessing facility per electricity generated	Land use per electricity generated	Water use per electricity generated	Carbon emission per electricity generated	Deployment difficulty of FOAK commercial-scale facilities
	SC11	SC21	SC22	SC23	SC24	SC31	SC41	SC42	SC51	SC52	SC53	SC61
A1	25.267	2.362	2.362	7.582E+03	22.778	54.776	0.030	0.000	0.011	3.203E+03	3.836E+06	1.000
A2	23.314	0.931	0.192	6.996E+03	20.837	55.257	0.024	0.358	0.009	2.951E+03	4.058E+06	1.002
A3	18.924	0.533	0.038	5.678E+03	16.803	55.725	0.012	0.450	0.007	2.948E+03	3.613E+06	1.012
A4	17.112	0.496	0.011	5.139E+03	15.305	56.605	0.011	0.265	0.006	3.196E+03	3.304E+03	1.007

3.2.1 Screening and ranking results

For PROMETHEE GAIA, an outranking model was first built using the PROMETHEE II method to calculate the net flow. In this model, we selected a level preference function to evaluate the quantitative criteria of MC1–5 (including their sub-criteria) and a V-shaped function for the qualitative criteria of MC6. Figure 7 shows the overall net ranking flow results for the four selected NFC alternatives. This indicates that the alternative ranking of prioritization, from highest to lowest, is as follows: A4, A1, A2, and A3. For A4, which involves direct spent fuel recycling in FRs, a compelling advantage to balancing its leaving and entering flows for net flow maximization is achieved.

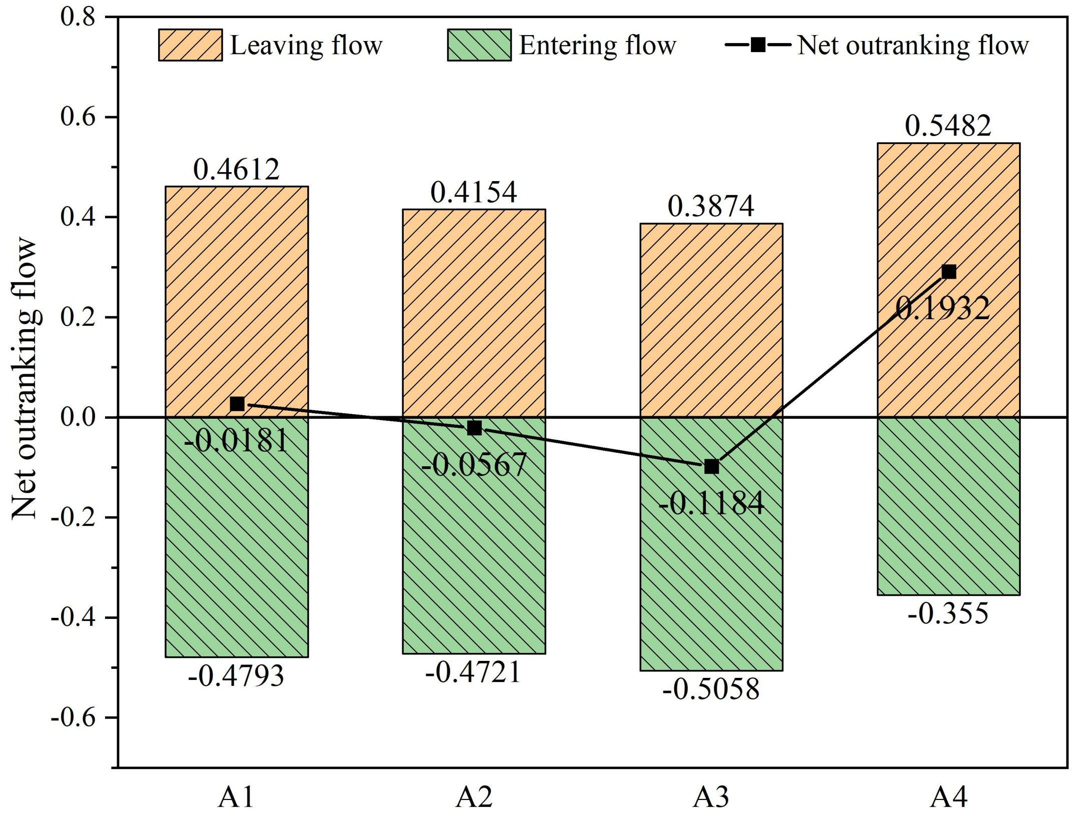


Figure 7 Net ranking flows of four alternatives

Figure 8 shows a GAIA plane with a quality of 97.2%, maintaining the most integrated information via a two-dimensional representation comprising both U and V, where U and V are the first and second principal components with the most valid information, respectively, and V possesses the maximum additional information orthogonal to U. As shown in Figure 8, the clubs and diamonds linked with black axes drawn from the center of the GAIA plane represent alternatives and criteria, respectively. The shades of the clubs are related to the

performances of the corresponding alternative; the darker the shade the better the performance of the club. The thick red axis represents the decision axis.

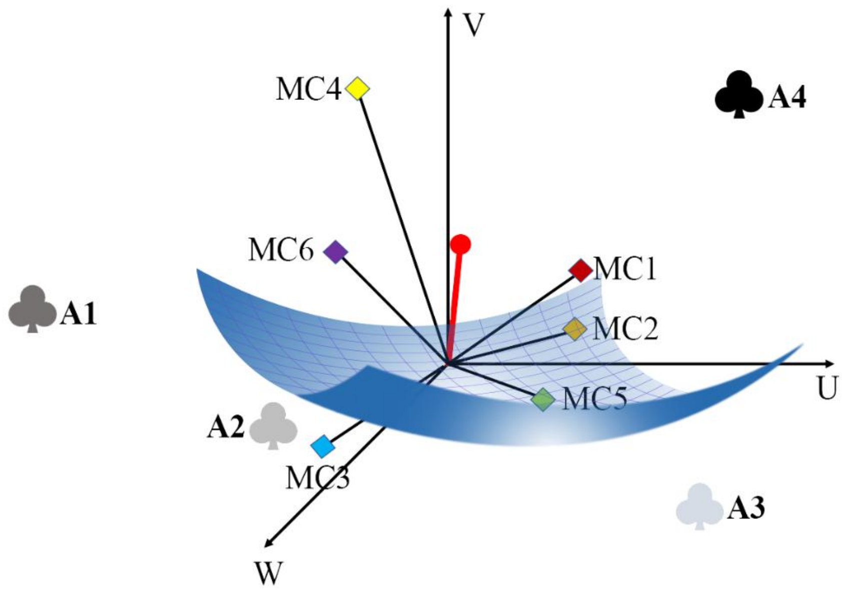


Figure 8 GAIA plane of four alternatives and six MC

The length of each axis indicates the relative importance of each criterion. For example, the axis of *MC5-Environmental impact* was the shortest because of its least assigned weight. The orientation of the axis can be applied to compare the effects of the criteria on the alternative evaluation. If the axes point in a parallel direction, their relevant criteria will have properties similar to those of the alternatives. For instance, both axes of *MC1-Resource utilization* and *MC2-Nuclear waste management* point in similar directions, implying that they could similarly influence the alternative evaluation. However, the resultant change caused by *MC1-Resource utilization* is slightly more significant than that of *MC2-Nuclear waste management* because the axis of the former is slightly longer. The dispersion of some axes in opposite directions indicates the presence of conflicting criteria such as *MC1-Resource utilization* and *MC3-Economics*, *MC5-Envrionmental impact*, and *MC6-Technological readiness*. Additionally, Figure 8 shows that A4 can be identified as the best compromise alternative because it is located within the area of decision axis points. This may be attributed to the relatively high performance of each conflict criterion.

Further, we analyzed the alternative performances of the different criteria separately through alternative positions with respect to the criteria axes. Figure 9 shows the U-V GAIA planes for the six MC cases, where the blue axis represents a certain criterion. When the projection of a certain alternative on the criteria axis close to the thick red

decision axis is relatively long, the performance of this alternative is better than that of the others. For *MC1-Resource utilization*, A4 was the preferred choice, while A1 was the worst. *MC2-Nuclear waste management* shares the same ranking results as *MC1-Resource utilization*, indicating that A4 performs the best in terms of both resource utilization and nuclear waste management. However, from an economic perspective (*MC3-Economics*), A1 is ranked first and A4 last. Furthermore, A1 adopts a favorable position under *MC4-Proliferatrion risk* and *MC6-Technological readiness*. Because the overall process of an NFC system is more complex and involves various species of nuclear fuels than others, A3 must address additional technological barriers while exiting higher nuclear proliferation risks. Therefore, A3 is the least competitive because of the importance of *MC4-Proliferation* and *MC6-Technological readiness*. However, when considering *MC5-Environmental impact*, the ranking result becomes the opposite: A3 is the best and A1 the worst.

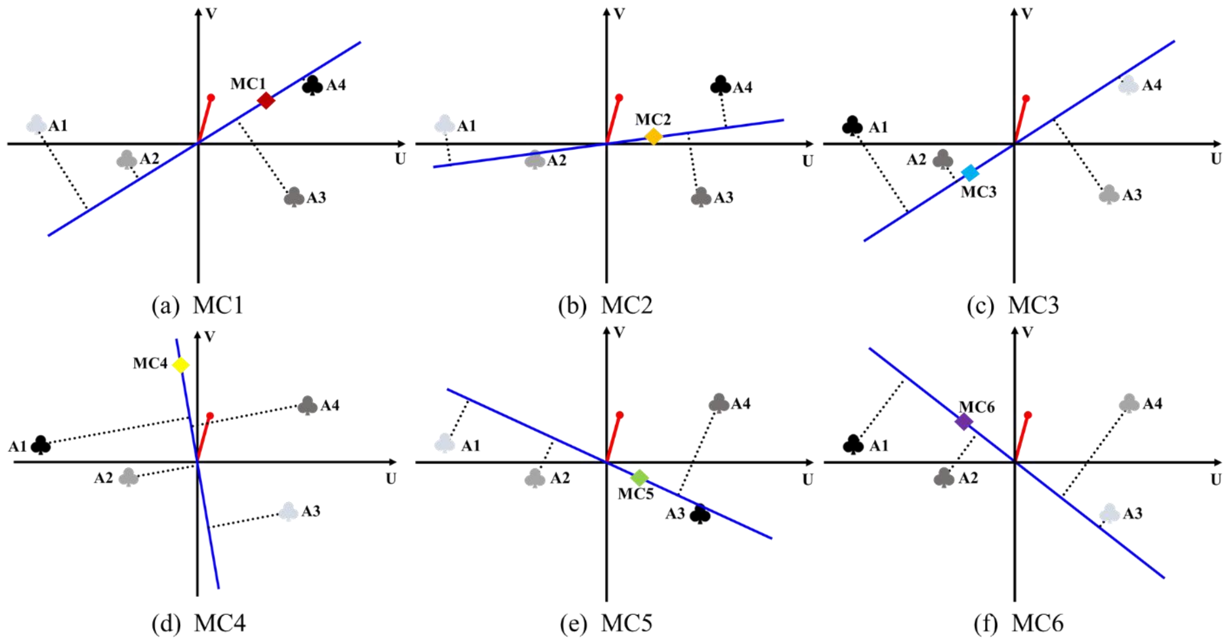


Figure 9 U-V GAIA plane of six MC

3.2.2 Sensitivity analysis

Using the relationship between criteria and alternatives shown in Figure 8, we conducted a sensitivity analysis of criteria weights to prove the effectiveness and robustness of the chosen preference relations and to validate the reliability of the overall MCDM framework. As shown in Figure 10, when the weight of a single criterion changes within a specially limited range and the weights of the other criteria are reassigned accordingly based on their previously specified proportions, as shown in Figure 6, the net ranking flows of the four alternatives can make a difference with no ranking reversals. The specifically limited range is termed the stability intervals of the criteria. Figure 11 shows the stability intervals of the six MC. The broader the stability range, the more stable the

corresponding criteria are against external interference.

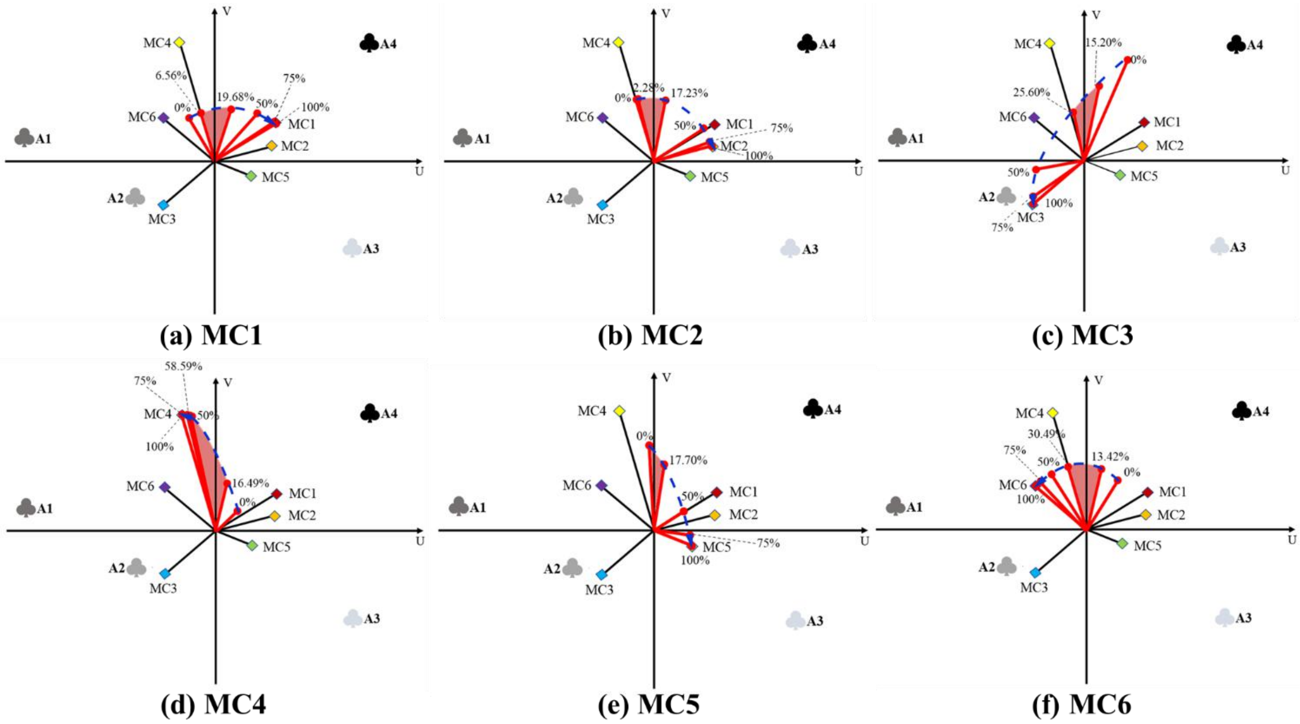


Figure 10 Trajectory of GAIA decision axis in the four alternatives influenced by indicator weights

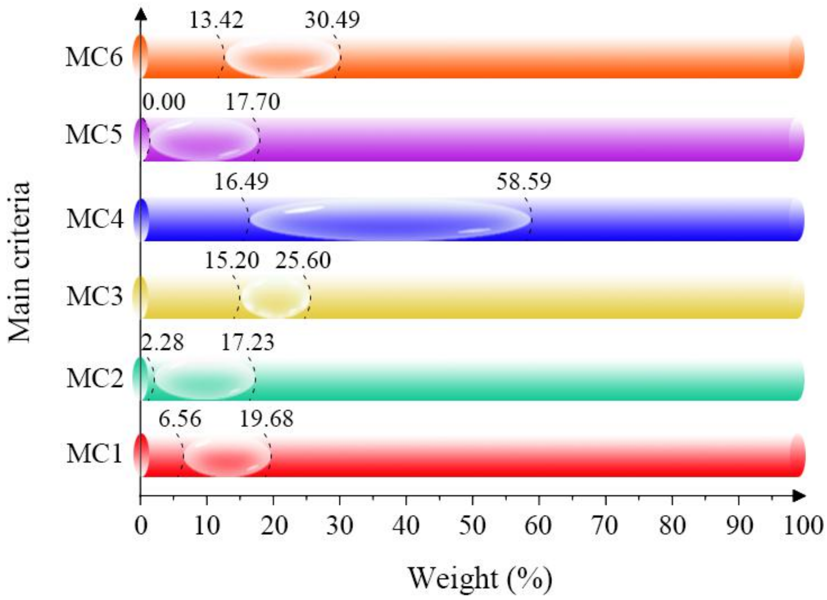


Figure 11 Weight stability interval of MC

The decision axis, which is an exclusive and flexible tool in PROMETHEE GAIA, is the visual pointing axis of the criteria weights located in the k-dimensional space of the GAIA plane. Its length, position, and orientation on the U-V plane depend only on its projection in a two-dimensional space. Its orientation can be used to determine only the optimal alternative; its length has no specific meaning because of the uncertainty and diversity of the

projection angle. The decision loses its effectiveness only when the length is extremely short. The decision axis is similar to the weighted average of the criteria axes; thus, a position change in the decision axis reflects the variance of the criteria weights intuitively. This is significant for detecting underweight or overweight criteria. When the criteria weight increases from zero, the decision axis begins to rotate toward the corresponding criteria axis with a length change until both axes coincide when the weight reaches 100%, as shown in Figure 10. The red shaded area indicates the stability interval of the designated criterion.

From the perspective of alternatives, the results show that A1 and A3 are sensitive to criteria weight changes, namely, larger uncertainties exist in assessing these two candidate NFC alternatives. On the contrary, A4 is the most insensitive candidate because its net outranking flow can always be the largest, regardless of the variances in the criteria weight.

For a certain criterion, when its weight changes within a range of 0-100%, a wide trajectory of the decision axis implies that it is less sensitive. As the weight of *MC1-Resource utilization* or *MC2-Nuclear waste management* increases, the decision axis turns in the same clockwise direction in the U-V GAIA plane, indicating that *MC1-Resource utilization* and *MC2-Nuclear waste management* can similarly influence these four alternatives. However, if the weight of *MC1-Resource utilization* or *MC2-Nuclear waste management* accounts for more than 50%, no changes in their final ranks are observed, with only a slight change in the outranking flow.

When strengthening the importance of *MC3-Economics*, the decision axis rotates counterclockwise in the two-dimensional U-V GAIA plane. This indicates that as DMs focus on economic issues, A1, which currently has an incomparable economic advantage, becomes the most optimal alternative rather than A4. However, when the weight of *MC3-Economics* increases to 47%, the length of the decision axis becomes the shortest, with a high uncertainty. This is a consequence of the internal interactions of conflicting criteria with an impact on alternatives. In such extreme circumstances, the credibility of the ranking results is compromised, and it is challenging to determine the best alternative.

When DMs focus on *MC4-Proliferation risk*, as shown in Figure 10, A1 still maintains the first rank among all the alternatives, its decision axis rotates in a counter-clockwise direction, and its length increases significantly with the largest weight stability interval (16.49-58.59%) compared with those of the other criteria. A broad stability interval indicates that proliferation risk cannot easily alter the overall ranking results of NFC alternatives.

However, when the weight of MC4 decreased from 16.49% to zero, A4 was the best option. Notably, its decision axis length became extremely small as the weight approached zero, leading to unreliable results. This in turn proves that the public cannot completely disregard nuclear security. Similarly, as the weight of MC6 increases, Figure 10 shows a similar trajectory of the decision axis as that of the MC4 case. However, the decision axis in the MC6 case was stable, and its length showed no noticeable change. This is mainly because of the differences in inherent characteristics and sensitivity to external disturbances between different criteria.

3.3 MOORA and optimization suggestions

The MOORA analysis provides a comparative evaluation to validate the above-mentioned screen results, ranking the four NFC alternatives in descending order of the final MOORA score y_i^*. The calculated results of the MOORA method are presented in Table 4. As aforementioned, A4 is the most suitable alternative, whereas the ranking of the other three alternatives has differences: A3 and A1 are ranked second and third, respectively, and A2 is considered the least preferred because it exhibits the weakest performance. Moreover, A4 gains a good ranking considering the benefits of NU conservation, nuclear waste management, and environmental impact reduction. However, the promising A4 cannot continuously assume the dominant position in all aspects because of its present performance. Combined with the MOORA results, we further analyzed the system optimization potential and provided some policy suggestions following the national strategy of nuclear energy.

Although progress has been made toward environmental sustainability, environmental issues have become a major concern in China. NU mining and milling activities have caused a significant impact on the environment, particularly in the processes of open-pit mining and open-air waste disposal, which use most of the land over the entire fuel cycle. The second contributor to land occupation is NPP construction and operation, and the final geological repository for nuclear waste contributes slightly [51]. Currently, China has become self-sufficient in most aspects of the fuel cycle. However, it still relies mostly on foreign uranium supply. Regarding the rapid expansion of nuclear power, the Chinese government has declared a future development plan for self-sufficient uranium production in cooperation with foreign suppliers. This plan includes at least one-third of domestic uranium production and two-thirds of Chinese equity in foreign mines and open uranium markets. Therefore, along with the growth in domestic uranium supply, the environmental impact caused by land use will increase accordingly. Compared with OT alternatives, A4 and other NFC paths with reprocessing and recycling processes can significantly reduce NU consumption, thus giving prominence to the future of small land occupations over

time.

Table 4 MOORA results

Alternative	SC11	SC21	SC22	SC23	SC24	SC31	SC41	SC42	SC51	SC52	SC53	SC61	y_{ij}^{*}	Rank
A1	113.9E-03	36.7E-03	35.9E-03	21.8E-03	20.2E-03	80.8E-03	15.8E-03	0	32.5E-03	31.2E-03	31.5E-03	75.1E-03	-0.495	3
A2	105.1E-03	14.5E-03	2.9E-03	20.1E-03	18.5E-03	81.5E-03	12.7E-03	85.4E-03	26.6E-03	28.8E-03	33.3E-03	75.3E-03	-0.505	4
A3	85.3E-03	8.27E-03	0.6E-03	16.4E-03	14.9E-03	82.2 -03	6.3E-03	107.3E-03	20.7E-03	28.7E-03	29.7E-03	76.0E-03	-0.476	2
A4	77.1E-03	7.70E-03	0.2E-03	14.8E-03	13.6E-03	83.5E-03	5.8E-03	63.2E-03	17.8E-03	31.2E-03	27.1E-03	75.6E-03	-0.418	1

In recent years, decarbonization has gradually become a global imperative for climate change mitigation, as the European Union has implemented a plan to render the entire community block free of CO_2 emissions by 2050 [6,52]. The Chinese government has proposed carbon peak and neutrality goals in close alignment with several countries, and the long-awaited carbon tax policy is yet to be implemented [53]. In the 14th Five-Year Plan, energy and climate were central policy priorities, and the National Energy Administration has proposed realistic plans for carbon reduction by the end of 2021 [54]. Recently, the Ministry of Ecology and Environment has deliberated and approved a series of administrative measures to promote the development of the national carbon emissions trading market, maximize the role of market mechanisms in addressing climate change, and encourage low-carbon technology innovation under green economic development [55-57]. As presented in Table 4, A4, which involves direct spent fuel recycling in fast reactors, has a comparative advantage in terms of reducing the life-cycle carbon emissions of the system. The active enforcement of emission–reduction policies and strategies, as well as the upcoming carbon tax, would provide potential incentives for all emitters to be responsible for increasingly expensive environmental costs, and the upcoming carbon tax could monetize environmental superiority. Although this inevitable trend is progressing, NFC innovation in the pursuit of a low-carbon development transition is urgently needed. However, solely relying on the low-carbon profit and NU conservation endowment of A4 is still insufficient to compensate for its overall low economic performance at the current stage. Normally, LRC accounts for more than 75–80% of the system's LCOE, whereas LFCC only contributes to the remaining 20–25%. Because of the high capital investment for NPP construction, especially for extremely expensive Gen-IV reactors with some major technological obstacles, the LRC in A4 and other advanced NFC systems may not easily be changed in a short time. In addition, the LFCC considerably influences the overall economic competitiveness of nuclear energy for different fuel cycle strategic priorities. The back-end fuel cycle costs in A2–4 are generally higher than those in A1 of the OT fuel cycle [41]. This might be partially attributed to the costly investment in complex facilities and technologies subject to reprocessing, including when offsets from decreased waste disposal costs are considered. Although advanced NESs are required to address multiple barriers, future nuclear energy will become technically feasible and economically attractive with innovation-driven development in China regarding domestic policy and market environments. Notably, an excessive pursuit of a new technology might be unnecessary and cost-expensive. An understanding of the near-term viability and long-term potential of advanced nuclear technologies, as well as their economic and technical contributions to the future energy market, should be established among DMs. "What's next for nuclear energy in China" should maintain flexibility and autonomy for future uncertainties through strategy, collaboration, and innovation while being complementary with variable renewables for securing a clean, affordable, reliable, and sustainable future energy system. An optimal transition alternative for NFC might not be a potential solution, as it leads to a continuous improvement in dynamic compliance with time.

4 Conclusions

In this study, we proposed a novel hybrid MCDM framework to assess China's potential NFC paths and identify an appropriate transition alternative for future sustainability-oriented NESs. Using the 6 MC and 12 SC from E-E-T dimensions, an improved fuzzy AHP method was used to obtain criteria weights under uncertainty, the PROMETHEE GAIA method was applied to determine the top-priority alternative, and an innovative MOORA

was adopted to provide a detailed comparative evaluation and analyze the system optimization potential.

Compared with existing studies, this study makes the following specific contributions:

1) Various weight aggregation and defuzzification approaches were applied to investigate the influence of the selection of different procedure methods within the fuzzy AHP model in detail.

2) The PROMETHEE method was employed to determine the preference priority using the highest to lowest net outranking flow values. Results showed that A4, which involves the OT fuel cycle followed by a direct reprocessing of PWR spent fuel in an FR, was the most suitable candidate alternative.

3) A GAIA method was used to address the conflicts among criteria and visualize the relationship between alternatives and criteria on a k-dimensional GAIA plane.

4) A sensitivity analysis was conducted to examine the decision axis trajectory affected by criteria weights and determine the weight stability interval.

5) Some optimization ideas and policies were suggested following the national strategy of nuclear energy for policymakers to make reliable decisions in evaluating NFC alternatives using the MOORA method.

Furthermore, the NFC assessment can be expanded to include alternatives and criteria. For example, environmental impacts, including nuclear waste radioactivity and decay heat, can be addressed and incorporated into a life cycle assessment. Additionally, particular multi-objective decision-making methods can be utilized to ensure an optimal configuration and operational strategy by establishing an optimization function from a mathematical point of view instead of MOORA.

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